

**"Theoretical and Observational Determination of
Global and Regional Radiation Budget, Forcing and
Feedbacks at the Top-of-Atmosphere and Surface"**

Final Summary of Research Report

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1. LIST OF ACCOMPLISHMENTS

- Improved the third-order turbulence closure in cloud resolving models to remove the liquid water oscillation.
- Developed a partially prognostic third-order closure model.
- Used the University of California-Los Angeles (UCLA) large-eddy simulation (LES) model to provide data for radiation transfer testing.
- Revised shortwave k-distribution models based on HITRAN 2000.
- Developed a gamma-weighted two-stream radiative transfer model for radiation budget estimate applications.
- Estimated the effect of spherical geometry to the earth radiation budget.
- Estimated top-of-atmosphere irradiance over snow and sea ice surfaces.
- Estimated the aerosol direct radiative effect at the top of the atmosphere.
- Estimated the top-of-atmosphere reflectance of the clear-sky molecular atmosphere over ocean.
- Developed and validated new set of Angular Distribution Models for the CERES TRMM satellite instrument (tropical)
- Developed and validated new set of Angular Distribution Models for the CERES Terra satellite instrument (global)
- Quantified the top-of-atmosphere direct radiative effect of aerosols over global oceans from merged CERES and MODIS observations
- Clarified the definition of TOA flux reference level for radiation budget studies
- Developed new algorithm for unfiltering CERES measured radiances
- Used multiangle POLDER measurements to produce narrowband angular distribution models and examine the effect of scene identification errors on TOA albedo estimates
- Developed and validated a novel algorithm called the Multidirectional Reflectance Matching (MRM) model for inferring TOA albedos from ice clouds using multi-angle satellite measurements.
- Developed and validated a novel algorithm called the Multidirectional Polarized Reflectance Matching (MPRM) model for inferring particle shapes from ice clouds using multi-angle polarized satellite measurements.
- Developed 4 advanced light scattering models including the three-dimensional (3D) uniaxial perfectly matched layer (UPML) finite-difference time-domain (FDTD) model.
- Develop sunglint in situ measurement and study reflectance distribution in the sunglint area.
- Lead a balloon-borne radiometer TOA albedo validation effort.
- Developed a CERES surface UVB, UVA, and UV index product.

2. LIST OF PUBLICATIONS (WHERE A CO-I IS LEAD AUTHOR)

- Cheng A., K.-M. Xu, and J.-C. Golaz, 2004: The liquid-water oscillation in modeling boundary-layer cumuli with third-order turbulence closure models. *J. Atmos. Sci.*, **61**, 1621-1629.
- Cheng A., 2004: Organization of Mesoscale Convective Systems (Part I: Numerical Experiments). *J. Geophys. Res.* (submitted).
- Cheng A., 2004: Organization of Mesoscale Convective Systems (Part II: Linear Theory), *J. Geophys. Res.* (submitted).
- Kato, S., N. G. Loeb, 2004: Top-of-atmosphere shortwave broadband observed radiance and estimated irradiance over polar regions from Clouds and the Earth's Radiant Energy System (CERES) instruments on Terra, *J. Geophys. Res.*, accepted for publication.
- Kato, S., and F. G. Rose, and T. P. Charlock, 2004: Computation of Domain-averaged Irradiance Using Satellite-derived Cloud Properties, *J. Atmos. Oceanic Technol.*, in press.
- Kato, S., and N. G. Loeb, 2003: Twilight irradiance reflected by the earth estimated from Clouds and the Earth's Radiant Energy System (CERES) measurements, *J. Climate*, **16**, 2646-2650.
- Kato, S. 2003: Computation of domain-averaged shortwave irradiance by a one-dimensional algorithm incorporating correlations between optical thickness and direct incident radiation, *J. Atmos. Sci.* **60**, 182-193.
- Kato, S., N. G. Loeb, and C. K. Rutledge, 2002: Estimate of top-of-atmosphere albedo for a molecular atmosphere over ocean using Clouds and the Earth's Radiant Energy System (CERES) measurements, *J. Geophys. Res.*, **107**, ACH10.
- Kato, S., G. L. Smith, and H. W. Barker, 2001: Gamma-weighted discrete ordinate two-stream approximation for computation of domain averaged solar irradiance, *J. Atmos. Sci.*, **58**, 3797-3803.
- Loeb, N.G., and N.M. Smith, 2004: Top-of-atmosphere direct radiative effect of aerosols over global oceans from merged CERES and MODIS observations, *J. Ocean and Atmos. Tech.* (submitted).
- Loeb, N.G., S. Kato, K. Loukachine, and N.M. Smith, 2004: Angular distribution models for top-of-atmosphere radiative flux estimation from the Clouds and the Earth's Radiant Energy System Instrument on the Terra Satellite. Part I: Methodology, *J. Ocean and Atmos. Tech.* (in press).
- Loeb, N.G., K. Loukachine, B.A. Wielicki, and D. F. Young, 2003: Angular distribution models for top-of-atmosphere radiative flux estimation from the Clouds and the Earth's Radiant Energy System instrument on the Tropical Rainfall Measuring Mission Satellite. Part II: Validation, *J. Appl. Meteor.*, **42**, 1748-1769.
- Loeb, N.G., N.M. Smith, S. Kato, W.F. Miller, S.K. Gupta, P. Minnis, and B.A. Wielicki, 2003: Angular distribution models for top-of-atmosphere radiative flux estimation from the Clouds and the Earth's Radiant Energy System instrument on the Tropical Rainfall Measuring Mission Satellite. Part I: Methodology, *J. Appl. Meteor.*, **42**, 240-265.
- Loeb, N.G., S. Kato, and B.A. Wielicki, 2002: Defining top-of-atmosphere flux reference level for Earth Radiation Budget studies, *J. Climate*, **15**, 3301-3309.

- Loeb, N.G. and S. Kato, 2002: Top-of-atmosphere direct radiative effect of aerosols from the Clouds and the Earth's Radiant Energy System Satellite instrument (CERES). *J. Climate*, **15**, 1474-1484.
- Loeb, N.G., K.J. Priestley, D.P. Kratz, E.B. Geier, R.N. Green, R.A. Wielicki, P. O'R. Hinton, and S.K. Nolan, 2001: Determination of unfiltered radiances from the Clouds and the Earth's Radiant Energy System (CERES) instrument. *J. Appl. Meteor.*, **40**, 822-835.
- Loeb, N.G., F. Parol, J.-C. Buriez, and C. Vanbaunce, 2000: Top-of-atmosphere albedo estimation from angular distribution models using scene identification from satellite cloud property retrievals. *J. Climate*, **13**, 1269-1285.
- Su, Wenying, T. P. Charlock, and Fred Rose, 2004, Deriving surface ultraviolet radiation from CERES surface and atmospheric budget, I: Methodology, *J. Geophys. Res.*, (submitted).
- Su, Wenying, T. P. Charlock, and Ken Rutledge, 2002, Observations of reflectance distribution around sunglint from a coastal ocean platform, *Appl. Opt.*, **41**, 7369-7383.
- Sun, W., N. G. Loeb, and P. Yang: On the retrieval of ice cloud particle shapes from POLDER measurements, *JQSRT* (in revision).
- Sun, W., N. G. Loeb, and B. Lin: Light scattering by an infinite circular cylinder immersed in an absorbing medium, *Appl. Opt.* (Accepted).
- Sun, W., N. G. Loeb, S. Tanev, and G. Videen: Finite-difference time domain solution of light scattering by an infinite dielectric column immersed in an absorbing medium, *Appl. Opt.* (Accepted).
- Sun, W., N. G. Loeb, and S. Kato, 2004: Estimation of instantaneous TOA albedo at 670 nm over ice clouds from POLDER multidirectional measurements, *J. Geophys. Res.*, **109**, D0221010.1029/2003JD003801.
- Sun, W., N. G. Loeb, G. Videen, and Q. Fu, 2004: Examination of surface roughness on light scattering by long ice columns by use of a two-dimensional finite-difference time-domain algorithm, *Appl. Opt.*, **43**, 1957-1964.
- Sun, W., N. G. Loeb, and Q. Fu, 2004: Light scattering by coated sphere immersed in absorbing medium: A comparison between the FDTD and analytic solutions, *JQSRT*, **83**, 483-492.
- Sun, W., T. Nousiainen, K. Muinonen, Q. Fu, N. G. Loeb, and G. Videen, 2003: Light scattering by Gaussian particles: A solution with finite-difference time domain technique, *JQSRT*, **79-80**, 1083-1090.
- Sun, W., N. G. Loeb, and Q. Fu, 2002: Finite-difference time domain solution of light scattering and absorption by particles in an absorbing medium, *Appl. Opt.*, **41**, 5728-5743.

3. ABSTRACTS OF PUBLISHED OR SUBMITTED PAPERS (WHERE A CO-I IS LEAD AUTHOR)

Cheng A., K.-M. Xu, and J.-C. Golaz, 2004: The liquid-water oscillation in modeling boundary-layer cumuli with third-order turbulence closure models. *J. Atmos. Sci.*, **61**, 1621-1629.

A hierarchy of third-order turbulence closure models are used to simulate boundary-layer cumuli in this study. An unrealistically strong liquid-water oscillation (LWO) is found in the fully prognostic model, which predicts all third moments. The LWO propagates from cloud base to cloud top with a speed of 1 m s^{-1} . The period of the oscillation is about 1000 s. Liquid-water buoyancy terms in the third-moment equations contribute to the LWO. The LWO mainly affects the vertical profiles of cloud fraction, mean liquid-water mixing ratio and the fluxes of liquid-water potential temperature and total water, but has less impact on the vertical profiles of other second-moments and third-moments.

In order to minimize the LWO, a moderate large diffusion coefficient and a large turbulent dissipation at its originating level are needed. However, this approach distorts the vertical distributions of cloud fraction and liquid-water mixing ratio. A better approach is to parameterize liquid-water buoyancy more reasonably. A minimally prognostic model, which diagnoses all third moments except for vertical velocity, is shown to produce better results, compared to a fully prognostic model.

Kato, S., N. G. Loeb, 2004: Top-of-atmosphere shortwave broadband observed radiance and estimated irradiance over polar regions from Clouds and the Earth's Radiant Energy System (CERES) instruments on Terra, *J. Geophys. Res.*, accepted for publication.

Empirical angular distribution models for estimating top-of-atmosphere shortwave irradiances from radiance measurements over permanent snow, fresh snow and sea ice are developed using CERES measurements on *Terra*. Permanent snow angular distribution models depend on cloud fraction, cloud optical thickness, and snow brightness. Fresh snow and sea ice angular distribution models depend on snow and sea ice fraction, cloud fraction, cloud optical thickness, and snow and ice brightness. These classifications lead to 10 scene types for permanent snow and 25 scene types for fresh snow and sea ice. The average radiance over clear-sky permanent snow is more isotropic with satellite viewing geometry than that over overcast permanent snow. On average, the albedo of clear-sky permanent snow varies from 0.65 to 0.68 for solar zenith angles between 60° and 80° , while the corresponding albedo of overcast scenes varies from 0.70 to 0.73.

Clear-sky permanent snow albedos over Antarctica estimated from two independent angular distribution models are consistent to within 0.6%, on average. Despite significant variability in sea ice optical properties with season, the estimated mean relative albedo error is -1 % for very dark sea ice and 0.1% for very bright sea ice when albedos derived from different viewing angles are averaged.

The estimated regional root-mean-square (RMS) relative albedo error is 5.6% and 2.6% when the sea ice angular distribution models are applied to a region that contains

very dark and very bright sea ice, respectively. Similarly, the estimated relative albedo bias error for fresh snow is -0.1% for very dark snow

Kato, S., and F. G. Rose, and T. P. Charlock, 2004: Computation of Domain-averaged Irradiance Using Satellite-derived Cloud Properties, *J. Atmos. Oceanic Technol.*, in press.

The respective errors caused by the gamma-weighted two-stream approximation and the effective thickness approximation for computing the domain-averaged broadband shortwave irradiance are evaluated using cloud optical thicknesses derived from one hour of radiance measurements by the Moderate Resolution Imaging Spectrometer (MODIS) over footprints of Clouds and the Earth's Radiant Energy System (CERES) instruments. Domains are CERES footprints of which dimension varies approximately from 20 to 70 km depending on the viewing zenith angle of the instruments.

The average error in the top-of-atmosphere irradiance at a 30° solar zenith angle caused by the gamma-weighted two-stream approximation is 6.1 W m^{-2} (0.005 albedo bias) with a one-layer overcast cloud where a positive value indicates overestimate by the approximation compared with the irradiance computed using the independent column approximation. Approximately the half of the error is due to deviations of optical thickness distributions from a gamma distribution and the other half of the error is due to other approximations in the model. The error increases to 14.7 W m^{-2} (0.012 albedo bias) when the computational layer dividing the cloud layer is increased to four. The increase is because of difficulties in treating the correlation of cloud properties in the vertical direction. Because the optical thickness under partly cloudy conditions, which contribute two-thirds of cloudy footprints, is smaller, the error is smaller than overcast conditions; the average error for partly cloud condition is -2.4 W m^{-2} (-0.002 albedo bias) at a 30° solar zenith angle. The corresponding average error caused by the effective thickness approximation is 0.5 W m^{-2} for overcast conditions and -21.5 W m^{-2} (-0.018 albedo bias) for partly cloudy conditions. Although the error caused by the effective thickness approximation depends strongly on the optical thickness, its average error under overcast conditions is smaller than the error caused by the gamma-weighted two-stream approximation because the errors at small and large optical thicknesses cancel each other. Based on these error analyses, the daily average error caused by the gamma-weighted two-stream and effective thickness approximations is less than 2 W m^{-2} .

Kato, S., and N. G. Loeb, 2003: Twilight irradiance reflected by the earth estimated from Clouds and the Earth's Radiant Energy System (CERES) measurements, *J. Climate*, **16**, 2646-2650.

The upward shortwave irradiance at the top of the atmosphere when the solar zenith angle is greater than 90° (twilight irradiance) is estimated from radiance measurements by the Clouds and the Earth's Radiant Energy System (CERES) instrument on the Tropical Rainfall Measuring Mission (TRMM) satellite.

The irradiance decreases with solar zenith angle from 7.5 W m^{-2} at 90.5° to 0.6 W m^{-2} at 95.5° . The global and daily average twilight irradiance is 0.2 W m^{-2} , which is three orders of magnitude smaller than the daily and global average reflected irradiance at the top of the atmosphere. Therefore, the twilight irradiance can be neglected in global radiation budget estimate. The daily average twilight irradiance, however, can be more

than 1 W m^{-2} at polar regions during seasons when the sun stays just below the horizon for a long period of time.

Kato, S. 2003: Computation of domain-averaged shortwave irradiance by a one-dimensional algorithm incorporating correlations between optical thickness and direct incident radiation, *J. Atmos. Sci.* **60**, 182-193.

A one-dimensional radiative transfer algorithm that accounts for correlations between the optical thickness and the incident direct solar radiation is developed to compute the domain-averaged shortwave irradiance profile. It divides the direct irradiance into four components and treats the direct irradiance in two separate, clear and cloudy columns to account for the fact that clouds attenuate the direct irradiance more than clear-sky. The horizontal inhomogeneity of clouds in the cloudy column is treated by the gamma weighted two-stream approximation, which assumes that the optical thickness of clouds follows a gamma distribution. The algorithm inputs the cloud fraction, cumulative cloud fraction as a function of height, and a parameter expressing the shape of the probability density function of the cloud optical thickness distribution in addition to inputs required for a two-stream radiative transfer model. These cloud property inputs can be obtained using ground- and satellite-based instruments. Therefore, the algorithm can treat realistic cloud overlap features and horizontal inhomogeneity of clouds in a framework of one-dimensional radiative transfer. Heating rates computed by the algorithm using cloud fields generated by cloud resolving models agree with those computed with a Monte Carlo model. If optical properties in computational layers that divide a vertically extensive cloud are correlated, the irradiance profile computed by the algorithm further improves.

Kato, S., N. G. Loeb, and C. K. Rutledge, 2002: Estimate of top-of-atmosphere albedo for a molecular atmosphere over ocean using Clouds and the Earth's Radiant Energy System (CERES) measurements, *J. Geophys. Res.* **107**, ACH10.

The shortwave broadband albedo at the top of a molecular atmosphere over ocean between 40° N and 40° S is estimated using radiance measurements from the Clouds and the Earth's Radiant Energy System (CERES) instrument and the Visible Infrared Scanner (VIRS) aboard the Tropical Rainfall Measuring Mission (TRMM) satellite. The albedo monotonically increases from 0.059 at a solar zenith angle of 10° to 0.107 at a solar zenith angle of 60° . The estimated uncertainty in the albedo is 3.5×10^{-3} caused by the uncertainty in CERES-derived irradiances, uncertainty in VIRS-derived aerosol optical thicknesses, variations in ozone and water vapor, and variations in surface wind speed. The estimated uncertainty is similar in magnitude to the standard deviation of 0.003 that is derived from 72 areas divided by 20° latitude by 20° longitude grid boxes. The empirically estimated albedo is compared with the modeled albedo using a radiative transfer model combined with an ocean surface bidirectional reflectivity model. The modeled albedo with standard tropical atmosphere is 0.061 and 0.111 at the solar zenith angles of 10° and 60° , respectively. This empirically estimated albedo can be used to estimate the direct radiative effect of aerosols at the top of the atmosphere over oceans.

Kato, S., G. L. Smith, and H. W. Barker, 2001: Gamma-weighted discrete ordinate two-stream approximation for computation of domain averaged solar irradiance, *J. Atmos. Sci.*, **58**, 3797-3803.

An algorithm is developed for the gamma-weighted discrete ordinate two-stream approximation that computes profiles of domain-averaged shortwave irradiances for horizontally inhomogeneous cloudy atmospheres. The algorithm assumes that frequency distributions of cloud optical depth at unresolved scales can be represented by a gamma distribution though it neglects net horizontal transport of radiation. This algorithm is an alternative to the one used in earlier studies that adopted the adding method. At present, only overcast cloudy layers are permitted.

Loeb, N.G., and N.M. Smith, 2004: Top-of-atmosphere direct radiative effect of aerosols over global oceans from merged CERES and MODIS observations, *J. Ocean and Atmos. Tech.* (submitted).

The direct radiative effect of aerosols (DREA) is defined as the difference between radiative fluxes in the absence and presence of aerosols. In this study, the direct radiative effect of aerosols is estimated for 46 months (March, 2000 to December, 2003) of merged CERES and MODIS Terra global measurements over ocean. This analysis includes the contribution from clear regions in both clear and partly cloudy CERES footprints. MODIS-CERES narrow-to-broadband regressions are developed to convert clear-sky MODIS narrowband radiances to broadband SW radiances, and CERES clear-sky Angular Distribution Models (ADMs) are used to estimate the corresponding TOA radiative fluxes needed to determine the DREA. Clear-sky MODIS pixels are identified using two independent cloud masks: (i) the NOAA-NESDIS algorithm used for inferring aerosol properties from MODIS on the CERES Single Scanner Footprint TOA/Surface Fluxes and Clouds (SSF) product (NOAA-SSF); and (ii) the standard algorithm used by the MODIS aerosol group to produce the MOD04 product (MOD04). Over global oceans, direct radiative cooling by aerosols for clear scenes identified from MOD04 is estimated to be 5.5 W m^{-2} , compared to 3.8 W m^{-2} for clear scenes from NOAA-SSF. Regionally, differences are largest in areas affected by dust aerosol, such as oceanic regions adjacent to the Saharan and Saudi Arabian deserts, and in northern Pacific Ocean regions influenced by dust transported from Asia. The net total-sky (clear and cloudy) DREA is negative (cooling) and is estimated to be -2.0 W m^{-2} from MOD04, and -1.6 W m^{-2} from NOAA-SSF. The DREA is shown to have pronounced seasonal cycles in the Northern Hemisphere and large year-to-year fluctuations near deserts. However, no systematic trend in deseasonalized anomalies of the DREA is observed over the 46-month time series considered.

Loeb, N.G., S. Kato, K. Loukachine, and N.M. Smith, 2004: Angular distribution models for top-of-atmosphere radiative flux estimation from the Clouds and the Earth's Radiant Energy System Instrument on the Terra Satellite. Part I: Methodology, *J. Ocean and Atmos. Tech.* (in press).

The Clouds and Earth's Radiant Energy System (CERES) provides coincident global cloud and aerosol properties together with reflected solar, emitted terrestrial longwave and infrared window radiative fluxes. These data are needed to improve our understanding and modeling of the interaction between clouds, aerosols and radiation at

the top of the atmosphere, surface, and within the atmosphere. This paper describes the approach used to estimate top-of-atmosphere (TOA) radiative fluxes from instantaneous CERES radiance measurements on the Terra satellite. A key component involves the development of empirical angular distribution models (ADMs) that account for the angular dependence of Earth's radiation field at the TOA. The CERES Terra ADMs are developed using 24 months of CERES radiances, coincident cloud and aerosol retrievals from the Moderate Resolution Imaging Spectroradiometer (MODIS), and meteorological parameters from the Global Modeling and Assimilation Office (GMAO)'s Goddard Earth Observing System DAS (GEOS-DAS V4.0.3) product. Scene information for the ADMs is from MODIS retrievals and GEOS-DAS V4.0.3 properties over ocean, land, desert and snow, for both clear and cloudy conditions. Because the CERES Terra ADMs are global, and far more CERES data is available on Terra than was available from CERES on the Tropical Rainfall Measuring Mission (TRMM), the methodology used to define CERES Terra ADMs is different in many respects from that used to develop CERES TRMM ADMs, particularly over snow/sea-ice, under cloudy conditions, and for clear scenes over land and desert.

Loeb, N.G., K. Loukachine, B.A. Wielicki, and D. F. Young, 2003: Angular distribution models for top-of-atmosphere radiative flux estimation from the Clouds and the Earth's Radiant Energy System instrument on the Tropical Rainfall Measuring Mission Satellite. Part II: Validation, *J. Appl. Meteor.*, **42**, 1748-1769.

Top-of-atmosphere (TOA) radiative fluxes from the Clouds and the Earth's Radiant Energy System (CERES) are estimated from empirical angular distribution models (ADMs) that convert instantaneous radiance measurements to TOA fluxes. This paper evaluates the accuracy of CERES TOA fluxes obtained from a new set of ADMs developed for the CERES instrument onboard the Tropical Rainfall Measuring Mission (TRMM). The uncertainty in regional monthly mean reflected shortwave (SW) and emitted longwave (LW) TOA fluxes is less than 0.5 W m^{-2} , based on comparisons with TOA fluxes evaluated by direct integration of the measured radiances. When stratified by viewing geometry, TOA fluxes from different angles are consistent to within 2% in the SW and 0.7% (or 2 W m^{-2}) in the LW. In contrast, TOA fluxes based on ADMs from the Earth Radiation Budget Experiment (ERBE) applied to the same CERES radiance measurements show a 10% relative increase with viewing zenith angle in the SW and a 3.5% (9 W m^{-2}) decrease with viewing zenith angle in the LW. Based on multiangle CERES radiance measurements, 18 regional instantaneous TOA flux errors from the new CERES ADMs are estimated to be 10 W m^{-2} in the SW and 3.5 W m^{-2} in the LW. The errors show little or no dependence on cloud phase, cloud optical depth, and cloud infrared emissivity. An analysis of cloud radiative forcing (CRF) sensitivity to differences between ERBE and CERES TRMM ADMs, scene identification, and directional models of albedo as a function of solar zenith angle shows that ADM and clear-sky scene identification differences can lead to an 8 W m^{-2} root-mean-square (rms) difference in 18 daily mean SW CRF and a 4 W m^{-2} rms difference in LW CRF. In contrast, monthly mean SW and LW CRF differences reach 3 W m^{-2} . CRF is found to be relatively insensitive to differences between the ERBE and CERES TRMM directional models.

Loeb, N.G., N.M. Smith, S. Kato, W.F. Miller, S.K. Gupta, P. Minnis, and B.A. Wielicki, 2003: Angular distribution models for top-of-atmosphere radiative flux estimation from the Clouds and the Earth's Radiant Energy System instrument on the Tropical Rainfall Measuring Mission Satellite. Part I: Methodology, *J. Appl. Meteor.*, **42**, 240-265.

Clouds and the Earth's Radiant Energy System (CERES) investigates the critical role that clouds and aerosols play in modulating the radiative energy flow within the Earth-atmosphere system. CERES builds upon the foundation laid by previous missions, such as the Earth Radiation Budget Experiment, to provide highly accurate top-of-atmosphere (TOA) radiative fluxes together with coincident cloud and aerosol properties inferred from high-resolution imager measurements. This paper describes the method used to construct empirical angular distribution models (ADMs) for estimating shortwave, longwave, and window TOA radiative fluxes from CERES radiance measurements on board the Tropical Rainfall Measuring Mission satellite. To construct the ADMs, multiangle CERES measurements are combined with coincident high-resolution Visible Infrared Scanner measurements and meteorological parameters from the European Centre for Medium-Range Weather Forecasts data assimilation product. The ADMs are stratified by scene types defined by parameters that have a strong influence on the angular dependence of Earth's radiation field at the TOA. Examples of how the new CERES ADMs depend upon the imager-based parameters are provided together with comparisons with existing models.

Loeb, N.G., S. Kato, and B.A. Wielicki, 2002: Defining top-of-atmosphere flux reference level for Earth Radiation Budget studies, *J. Climate*, **15**, 3301-3309.

To estimate the earth's radiation budget at the top of the atmosphere (TOA) from satellite-measured radiances, it is necessary to account for the finite geometry of the earth and recognize that the earth is a solid body surrounded by a translucent atmosphere of finite thickness that attenuates solar radiation differently at different heights. As a result, in order to account for all of the reflected solar and emitted thermal radiation from the planet by direct integration of satellite-measured radiances, the measurement viewing geometry must be defined at a reference level well above the earth's surface (e.g., 100 km). This ensures that all radiation contributions, including radiation escaping the planet along slant paths above the earth's tangent point, are accounted for. By using a field-of-view (FOV) reference level that is too low (such as the surface reference level), TOA fluxes for most scene types are systematically underestimated by 1–2 W m⁻². In addition, since TOA flux represents a flow of radiant energy per unit area, and varies with distance from the earth according to the inverse-square law, a reference level is also needed to define satellite-based TOA fluxes. From theoretical radiative transfer calculations using a model that accounts for spherical geometry, the optimal reference level for defining TOA fluxes in radiation budget studies for the earth is estimated to be approximately 20 km. At this reference level, there is no need to explicitly account for horizontal transmission of solar radiation through the atmosphere in the earth radiation budget calculation. In this context, therefore, the 20-km reference level corresponds to the effective radiative “top of atmosphere” for the planet. Although the optimal flux reference level depends slightly on scene type due to differences in effective transmission of solar radiation with cloud height, the difference in flux caused by neglecting the scene-type dependence is less than

0.1%. If an inappropriate TOA flux reference level is used to define satellite TOA fluxes, and horizontal transmission of solar radiation through the planet is not accounted for in the radiation budget equation, systematic errors in net flux of up to 8 W m^{-2} can result. Since climate models generally use a plane-parallel model approximation to estimate TOA fluxes and the earth radiation budget, they implicitly assume zero horizontal transmission of solar radiation in the radiation budget equation, and do not need to specify a flux reference level. By defining satellite-based TOA flux estimates at a 20-km flux reference level, comparisons with plane-parallel climate model calculations are simplified since there is no need to explicitly correct plane-parallel climate model fluxes for horizontal transmission of solar radiation through a finite earth.

Loeb, N.G. and S. Kato, 2002: Top-of-atmosphere direct radiative effect of aerosols from the Clouds and the Earth's Radiant Energy System Satellite instrument (CERES). *J. Climate*, **15**, 1474-1484.

Nine months of CERES/TRMM broadband fluxes combined with VIRS high-resolution imager measurements are used to estimate the daily average direct radiative effect of aerosols for clear-sky conditions over the tropical oceans. On average, aerosols have a cooling effect over the tropics of $4.6 \pm 1 \text{ W m}^{-2}$. The magnitude is $\approx 2 \text{ W m}^{-2}$ smaller over the southern tropical oceans than it is over northern tropical oceans. The direct effect derived from CERES is highly correlated with coincident aerosol optical depth retrievals inferred from $0.63 \mu\text{m}$ VIRS radiances (correlation coefficient of 0.96). The slope of the regression line is $\approx 32 \text{ W m}^{-2} \tau^{-1}$ over the equatorial Pacific Ocean, but changes both regionally and seasonally, depending on the aerosol characteristics. Near sources of biomass burning and desert dust, the aerosol direct effect reaches -25 W m^{-2} to -30 W m^{-2} . The direct effect from CERES also shows a dependence on wind speed. The reason for this dependence is unclear—it may be due to increased aerosol (e.g. sea-salt or aerosol transport) or increased surface reflection (e.g. due to whitecaps). The uncertainty in the tropical average direct effect from CERES is $\approx 1 \text{ W m}^{-2}$ ($\approx 20\%$) due mainly to cloud contamination, the radiance-to-flux conversion, and instrument calibration. By comparison, uncertainties in the direct effect from the ERBE and CERES "ERBE-Like" products are a factor of 3 to 5 larger.

Loeb, N.G., K.J. Priestley, D.P. Kratz, E.B. Geier, R.N. Green, B.A. Wielicki, P. O'R. Hinton, and S.K. Nolan, 2001: Determination of unfiltered radiances from the Clouds and the Earth's Radiant Energy System (CERES) instrument. *J. Appl. Meteor.*, **40**, 822-835.

A new method for determining unfiltered shortwave (SW), longwave (LW) and window (WN) radiances from filtered radiances measured by the Clouds and the Earth's Radiant Energy System (CERES) satellite instrument is presented. The method uses theoretically derived regression coefficients between filtered and unfiltered radiances that are a function of viewing geometry, geotype and whether or not cloud is present. Relative errors in instantaneous unfiltered radiances from this method are generally well below 1% for SW radiances ($\approx 0.4\%$ 1σ or $\approx 1 \text{ W m}^{-2}$ equivalent flux), $< 0.2\%$ for LW radiances ($\approx 0.1\%$ 1σ or $\approx 0.3 \text{ W m}^{-2}$ equivalent flux) and $< 0.2\%$ ($\approx 0.1\%$ 1σ) for window channel radiances.

When three months (June, July and August 1998) of CERES ERBE-Like unfiltered radiances from the Tropical Rainfall Measuring Mission (TRMM) satellite between 20°S and 20°N are compared with archived Earth Radiation Budget Satellite (ERBS) scanner measurements for the same months over a five year period (1985-1989), significant scene-type dependent differences are observed in the SW channel. Full-resolution CERES SW unfiltered radiances are $\approx 7.5\%$ ($\approx 3 \text{ W m}^{-2}$ equivalent diurnal average flux) lower than ERBS over clear ocean, compared to $\approx 1.7\%$ ($\approx 4 \text{ W m}^{-2}$ equivalent diurnal average flux) for deep convective clouds, and $\approx 6\%$ ($\approx 4\text{-}6 \text{ W m}^{-2}$ equivalent diurnal average flux) for clear land and desert. This dependence on scene type is shown to be partly caused by differences in spatial resolution between CERES and ERBS, and because of errors in the unfiltering method used in ERBS. When the CERES measurements are spatially averaged to match the ERBS spatial resolution, and the unfiltering scheme proposed in this study is applied to both CERES and ERBS, the ERBS all-sky SW radiances increase by $\approx 1.7\%$, and the CERES radiances are now consistently $\approx 3.5\%$ - 5% lower than the modified ERBS values for all scene types. Further study is needed to determine the cause for this remaining difference, and even calibration errors cannot be ruled out. In the LW, CERES LW radiances are closer to ERBS values for individual scene types—CERES radiances are within $\approx 0.1\%$ ($\approx 0.3 \text{ W m}^{-2}$) of ERBS over clear ocean, and $\approx 0.5\%$ ($\approx 1.5 \text{ W m}^{-2}$) over clear land and desert. Because of large differences in the frequency of occurrence of the individual scene types between CERES and ERBS, differences in all-sky radiances are much larger—daytime LW radiances from CERES are $\approx 1.1\%$ ($\approx 3 \text{ W m}^{-2}$) larger than ERBS archived values; at night, CERES radiances are larger by $\approx 2.1\%$ ($\approx 5 \text{ W m}^{-2}$).

Loeb, N.G., F. Parol, J.-C. Buriez, and C. Vanbaune, 2000: Top-of-atmosphere albedo estimation from angular distribution models using scene identification from satellite cloud property retrievals. *J. Climate*, **13**, 1269-1285.

The next generation of Earth radiation budget satellite instruments will routinely merge estimates of global top-of-atmosphere radiative fluxes with cloud properties. This information will offer many new opportunities for validating radiative transfer models and cloud parameterizations in climate models. In this study, five months of POLarization and Directionality of the Earth's Reflectances (POLDER) 670 nm radiance measurements are considered in order to examine how satellite cloud property retrievals can be used to define empirical Angular Distribution Models (ADMs) for estimating top-of-atmosphere (TOA) albedo. ADMs are defined for 19 scene types defined by satellite retrievals of cloud fraction and cloud optical depth. Two approaches are used to define the ADM scene types: The first assumes there are no biases in the retrieved cloud properties and defines ADMs for fixed discrete intervals of cloud fraction and cloud optical depth (fixed- τ approach). The second approach involves the same cloud fraction intervals, but uses *percentile* intervals of cloud optical depth instead (percentile- τ approach). Albedos generated using these methods are compared with albedos inferred directly from the mean observed reflectance field.

Albedos based on ADMs that assume cloud properties are unbiased (fixed- τ approach) show a strong systematic dependence on viewing geometry. This dependence becomes more pronounced with increasing solar zenith angle, reaching $\approx 12\%$ (relative)

between near-nadir and oblique viewing zenith angles for solar zenith angles between 60° and 70°. The cause for this bias is shown to be due to biases in the cloud optical depth retrievals. In contrast, albedos based on ADMs built using *percentile* intervals of cloud optical depth (percentile- τ approach) show very little viewing zenith angle dependence and are in good agreement with albedos obtained by direct integration of the mean observed reflectance field (< 1% relative error). When the ADMs are applied separately to populations consisting of only liquid water and ice clouds, significant biases in albedo with viewing geometry are observed (particularly at low sun elevations), highlighting the need to account for cloud phase both in cloud optical depth retrievals and in defining ADM scene types. ADM-derived monthly mean albedos determined for all 5°×5° latitude/longitude regions over ocean are in good agreement (regional RMS relative errors < 2%) with those obtained by direct integration when ADM albedos inferred from specific angular bins are averaged together. Albedos inferred from near-nadir and oblique viewing zenith angles are the least accurate, with regional RMS errors reaching ~5-10% (relative). Compared to an earlier study involving ERBE ADMs, regional mean albedos based on the 19 scene types considered here show a factor of 4 reduction in bias error and a factor of 3 reduction in RMS error.

Su, W., T. P. Charlock, and F. Rose, 2004: Deriving surface ultraviolet radiation from CERES surface and atmospheric budget, I: Methodology, *J. Geophys. Res.*, (submitted).

We describe an algorithm that retrieves the surface UVB (280-315 nm) and UVA (315-400 nm) irradiances from the Clouds and the Earth's Radiant Energy System (CERES) instruments. The algorithm uses two UV spectral bands of the CERES Surface and Atmosphere Radiation Budget (SARB) product to generate surface UVB and UVA irradiances from a set of ratio lookup tables that we created. We show that the ratio of Band 5 to UVB irradiance is sensitive to total column ozone, solar zenith angle, surface albedo, and the atmospheric profile in cloud-free conditions; in cloudy conditions, the ratio of Band 5 to UVB irradiance is also sensitive to cloud optical depth and height. Additionally, we show that the ratio of Band 6 to UVA irradiance is sensitive to solar zenith angle, surface albedo, and cloud optical depth. We also derive a UV index from the UVB irradiance. Our algorithm may be applied at any surface elevation or surface type, including snow and ice. Surface UV irradiances derived from the lookup table that we created agree well with those computed by a multistream radiative transfer code, with differences ranging from -10 to +4 percent for UVB and UVA irradiances. The relative differences for the UV index are higher, ranging from -26 to +16 percent.

Su, W., T. P. Charlock, and K. Rutledge, 2002: Observations of reflectance distribution around sunglint from a coastal ocean platform, *Appl. Opt.*, **41**, 7369-7383.

A scanning spectral photometer is deployed on a rigid coastal ocean platform to measure upwelling solar radiances from the sea surface at nine elevation angles spanning 150° of azimuth. Measured radiance distributions at 500 nm wavelength have been compared with traditional model simulations employing the Cox and Munk distribution of wave slopes. The model captures the general features of the observed angular reflectance distributions, but: a the observed peak value of sunglint near the specular direction is larger than simulated, except for a very calm sea; the model-measurement

differences increase with wind speed and are largest for low solar elevation; but the observed sunglint is wider than simulated. In contrast to some previous studies, our results do not show a clear dependence of the mean square sea-surface slope on stability air-sea temperature difference.

Sun, W., N. G. Loeb, and P. Yang, 2004: On the retrieval of ice cloud particle shapes from POLDER measurements, *JQSRT* (in revision).

Shapes of ice crystals can significantly affect the radiative transfer in ice clouds. The angular distribution of the polarized reflectance over ice clouds strongly depends on ice crystal shapes. Although the angular-distribution features of the total or polarized reflectance over ice clouds implies a possibility of retrieving ice cloud particle shapes by use of remote sensing data, the accuracy of the retrieval must be evaluated. In this study, a technique, which applies single ice crystal habit and multidirectional polarized radiance to retrieve ice cloud particle shapes, is assessed. Our sensitivity studies show that the retrieved particle shapes from this algorithm can be considered good approximations to those in actual clouds in calculation of the phase matrix elements. Although a fractal poly-crystal shape or an inhomogeneous hexagonal column may also produce this type of phase functions, more representative single-scattering properties from combinations of natural particle shapes and size distributions may still be necessary in accurate retrieval of other cloud properties such as optical thickness and particle size.

Sun, W., N. G. Loeb, and B. Lin, 2004: Light scattering by an infinite circular cylinder immersed in an absorbing medium, *Appl. Opt.* (Accepted).

Analytic solutions are developed for the single-scattering properties of an infinite dielectric cylinder embedded in an absorbing medium with normal incidence, which include extinction, scattering and absorption efficiencies, the scattering phase function, and the asymmetry factor. The extinction and scattering efficiencies are derived by the near-field solutions at the surface of the particle. The normalized scattering phase function is obtained by use of the far-field approximation. Computational results show that while the absorbing medium significantly reduces the scattering efficiency, it has little effect on absorption efficiency. The absorbing medium can significantly change the conventional phase function. The absorbing medium also strongly affects the polarization of the scattered light. However, for large absorbing particles the degrees of polarization change little with the medium's absorption. This implies that if the transmitting lights are strongly weakened inside the particle the scattered polarized lights can be used to identify objects even when the absorption property of the host medium is unknown, which is very important for both active and passive remote sensing.

Sun, W., N. G. Loeb, S. Tanev, and G. Videen, 2004: Finite-difference time domain solution of light scattering by an infinite dielectric column immersed in an absorbing medium, *Appl. Opt.* (Accepted).

The two-dimensional (2-D) finite-difference time domain (FDTD) method is applied to calculate light scattering and absorption by an arbitrarily shaped infinite column embedded in an absorbing dielectric medium. A uniaxial perfectly matched layer (UPML) absorbing boundary condition (ABC) is used to truncate the computational domain. The single-scattering properties of the infinite column embedded in the absorbing medium, including scattering phase functions, extinction and absorption

efficiencies, are derived using an area integration of the internal field. An exact solution for light scattering and absorption by a circular cylinder in an absorbing medium is used to examine the accuracy of the 2-D UPML FDTD code. With use of a cell size of $1/120$ incident wavelength in the FDTD calculations, the errors in the extinction and absorption efficiencies and asymmetry factors from the 2-D UPML FDTD are generally smaller than $\sim 0.1\%$. The errors in the scattering phase functions are typically smaller than $\sim 4\%$. Using the 2-D UPML FDTD technique, light scattering and absorption by long noncircular columns embedded in absorbing media can be accurately solved.

Sun, W., N. G. Loeb, and S. Kato, 2004: Estimation of instantaneous TOA albedo at 670 nm over ice clouds from POLDER multidirectional measurements, *J. Geophys. Res.*, **109**, D0221010.1029/2003JD003801.

An algorithm that determines the 670-nm top-of-atmosphere (TOA) albedo of ice clouds over ocean using Polarization and Directionality of the Earth's Reflectance (POLDER) multidirectional measurements is developed. A plane-parallel layer of ice cloud with various optical thicknesses and light scattering phase functions is assumed. For simplicity, we use a double Henyey-Greenstein phase function to approximate the volume-averaged phase function of the ice clouds. A multidirectional reflectance best-fit match between theoretical and POLDER reflectances is used to infer effective cloud optical thickness, phase function and TOA albedo. Sensitivity tests show that while the method does not provide accurate independent retrievals of effective cloud optical depth and phase function, TOA albedo retrievals are accurate to within similar to 3% for both a single layer of ice clouds or a multilayer system of ice clouds and water clouds. When the method is applied to POLDER measurements and retrieved albedos are compared with albedos based on empirical angular distribution models (ADMs), zonal albedo differences are generally smaller than similar to 3%. When albedos are compared with those on the POLDER-I ERB and Cloud product, the differences can reach similar to 15% at small solar zenith angles.

Sun, W., N. G. Loeb, G. Videen, and Q. Fu, 2004: Examination of surface roughness on light scattering by long ice columns by use of a two-dimensional finite-difference time-domain algorithm, *Appl. Opt.*, **43**, 1957-1964.

Natural particles such as ice crystals in cirrus clouds generally are not pristine but have additional microroughness on their surfaces. A two-dimensional finite-difference time-domain (FDTD) program with a perfectly matched layer absorbing boundary condition is developed to calculate the effect of surface roughness on light scattering by long ice columns. When we use a spatial cell size of $1/120$ incident wavelength for ice circular cylinders with size parameters of 6 and 24 at wavelengths of 0.55 and 10.8 μm , respectively, the errors in the FDTD results in the extinction, scattering, and absorption efficiencies are smaller than similar to 0.5%. The errors in the FDTD results in the asymmetry factor are smaller than similar to 0.05%. The errors in the FDTD results in the phase-matrix elements are smaller than similar to 5%. By adding a pseudorandom change as great as 10% of the radius of a cylinder, we calculate the scattering properties of randomly oriented rough-surfaced ice columns. We conclude that, although the effect of small surface roughness on light scattering is negligible, the scattering phase-matrix elements change significantly for particles with large surface roughness. The roughness on the particle surface can make the conventional phase function smooth. The most

significant effect of the surface roughness is the decay of polarization of the scattered light.

Sun, W., N. G. Loeb, and Q. Fu, 2004: Light scattering by coated sphere immersed in absorbing medium: A comparison between the FDTD and analytic solutions, *JQSRT*, **83**, 483-492.

A recently developed finite-difference time domain scheme is examined using the exact analytic solutions for light scattering by a coated sphere immersed in an absorbing medium. The relative differences are less than 1% in the extinction, scattering, and absorption efficiencies and less than 5% in the scattering phase functions. The definition of apparent single-scattering properties is also discussed. (C) 2003 Elsevier Ltd. All rights reserved.

Sun, W., T. Nousiainen, K. Muinonen, Q. Fu, N. G. Loeb, and G. Videen, 2003: Light scattering by Gaussian particles: A solution with finite-difference time domain technique, *JQSRT*, **79-80**, 1083-1090.

The understanding of single-scattering properties of complex ice crystals has significance in atmospheric radiative transfer and remote-sensing applications. In this work, light scattering by irregularly shaped Gaussian ice crystals is studied with the finite-difference time-domain (FDTD) technique. For given sample particle shapes and size parameters in the resonance region, the scattering phase matrices and asymmetry factors are calculated. It is found that the deformation of the particle surface can significantly smooth the scattering phase functions and slightly reduce the asymmetry factors. The polarization properties of irregular ice crystals are also significantly different from those of spherical cloud particles. These FDTD results could provide a reference for approximate light-scattering models developed for irregular particle shapes and can have potential applications in developing a much simpler practical light scattering model for ice clouds angular-distribution models and for remote sensing of ice clouds and aerosols using polarized light. (C) 2003 Elsevier Science Ltd. All rights reserved.

Sun, W., N. G. Loeb, and Q. Fu, 2002: Finite-difference time domain solution of light scattering and absorption by particles in an absorbing medium, *Appl. Opt.*, **41**, 5728-5743.

The three-dimensional (3-D) finite-difference time-domain (FDTD) technique has been extended to simulate light scattering and absorption by nonspherical particles embedded in an absorbing dielectric medium. A uniaxial perfectly matched layer (UPML) absorbing boundary condition is used to truncate the computational domain. When computing the single-scattering properties of a particle in an absorbing dielectric medium, we derive the single-scattering properties including scattering phase functions, extinction, and absorption efficiencies using a volume integration of the internal field. A Mie solution for light scattering and absorption by spherical particles in an absorbing medium is used to examine the accuracy of the 3-D UPML FDTD code. It is found that the errors in the extinction and absorption efficiencies from the 3-D UPML FDTD are less than similar to 2%. The errors in the scattering phase functions are typically less than similar to 5%. The errors in the asymmetry factors are less than similar to 0.1%. For light scattering by particles in free space, the accuracy of the 3-D UPML FDTD scheme is similar to a previous model. [*Appl. Opt.*, **38**, 3141 (1999)].

4. SUBJECT INVENTION DISCLOSURE

There are no inventions to be disclosed for this investigation.